On-Line Measurement of Moisture Content of Iron Ore Slurries

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Contents

Nomenclature

A: Attenuation

C_1 and C_2: Parameters included in the density independent function which connects moisture content to phase shift and attenuation

M: Moisture content of iron ore slurries.

P: Microwave power

P_0: Microwave power in the free space

X: The ratio between phase shift ϕ and attenuation A

d: Bed depth

ϕ: Phase shift

ϵ^*: Permittivity

ϵ': Dielectric constant. Real part of the permittivity expression

ϵ'': Loss factor. Imaginary part of the permittivity expression

ϵ_r^*: Relative permittivity

ϵ_0: Permittivity of free space. It has a value of $8.854 \times 10^{-12} F/m$

μ: Permeability

γ: Propagation constant

α: Attenuation constant

β: Phase shift constant

μ^*: Permeability of a nonmagnetic material at magnetic field

μ_0: Vacuum permeability

λ: Wave length

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Abstract

This report presents a method of measuring moisture content in iron ore slurries using the application of microwave. The composition of iron ore slurries consists of magnetite, hematite, calcium carbonate, magnesium carbonate, siderite, alumina, silica, and water. When being placed in an electromagnetic field, interactions will happen between the slurry components and the field. Permittivity ϵ^* is the main parameter to describe these interactions. Since water has the largest dielectric constant compared with other materials, the water content of the material can be estimated from measured permittivity values. For each species, attenuation and microwave phase shift are two intermediate functions related to permittivity, temperature and bed depth when a microwave is passing through particles on conveyor belt. According to theory, a linear model is expected between the materials' moisture content and the ratio of attenuation and phase shift.

Introduction

Most natural products contain moisture, and water content can affect cost, quality and production. Moisture analysis helps manufacturers control the quality of their output. A variety of industries are concerned with moisture analysis, such as agriculture, food and mining.

In the mining industry, moisture levels in the ore should be kept within a certain limit, known as the dust extinction moisture (DEM) level. If the water added exceeds the DEM, the ore tends to swell, becoming sticky with the addition of bentonite binder. If even more water is added, the material can become unstable and collapse. But if the moisture content is low, too much dust may form that can damage or impair equipment and technology. In addition, it can cause health and environment pollution problems. Therefore, maintaining the appropriate moisture content throughout iron ore production is critical.

Currently, the primary method of measuring moisture content in mineral industry is taking a certain mass of sample to the laboratory, weighing the sample without drying and reweighing it

after 100% water evaporation. Water content is simply the mass difference between the two tests. However, disadvantages are obvious for the lab method, such as the measurement process is time consuming and the results are not representative of on-line values.

With the introduction of on-line moisture measurement technologies, the control of the production process will be more effective. Following are advantages for on-line measurement of moisture content:

- Results are consistent and representative
- Loss of the sample is minimized
- Providing instant and reliable information
- No human factors during the measurement process

There exist various technologies for the on-line measurement of water content. These include contact probes, such as conductivity, capacitance or drag force meters, as well as non-contact methods, such as infrared analysis of the material surface. Transmission microwave analysis involves the transmission of a microwave beam from one side of the material, and detection of the phase and amplitude of the portion of the beam exiting from the other side of the material. However, some difficulties exist for minerals applications. For instance, conveyor bed depths may be over 400mm, particle size may exceed 100mm, belt speeds may be relatively fast and the measurement environment may be dusty. These harsh conditions result in the failure of installation of contact methods; meanwhile, infrared analysis is only able to measure surface water of the material. Therefore, microwave technology, if workable, is a more logical choice for minerals application. Here listed some features of microwave radiation:

- Wave propagation direction is a straight line and it obeys the laws of optic.
- Microwaves can propagate through free space; thus, a physical contact between the equipment and the material under test is not required, allowing remote sensing to be accomplished.
- Many solid dielectric materials are opaque to light and infrared radiation but transparent to microwaves, which permits the probing of the whole volume of material transported inside dielectric tubing without the need for special windows.

- Microwave radiation does not alter or contaminate the material under test as do some chemical methods, enabling fast, nonconductive, and continuous monitoring (Kraszewski, 1996).

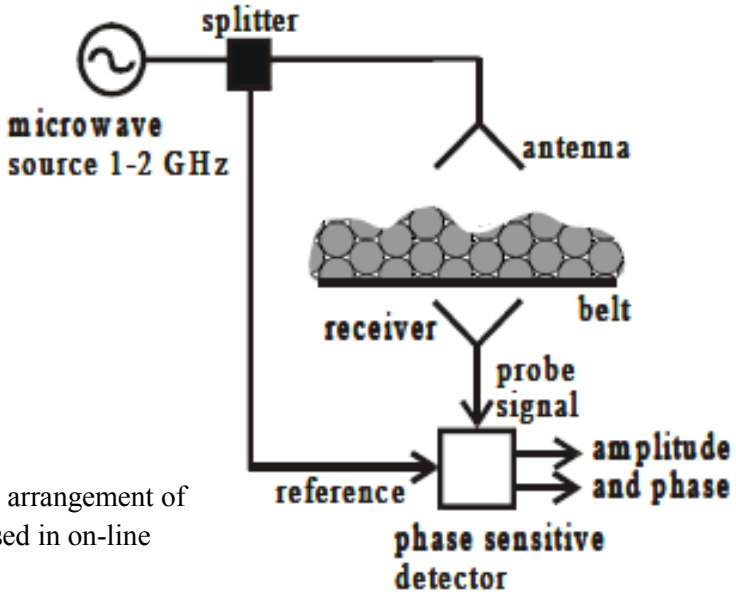

Figure 1. Schematic arrangement of the interferometer used in on-line moisture analysers.

Theory

Previous studies based on the moisture content of other materials, such as wheat, provide a reliable correlation formula between moisture content and the ratio of two measured parameters. It is displayed as:

$$\frac{1}{X} = C_1 \times M + C_2 \quad (1)$$

$$X = \frac{\phi}{A} \quad (2)$$

where X is the ratio between phase shift, ϕ, and attenuation, A. C_1 and C_2 are two coefficient determined by experiments. M is the relative moisture content and it is a unitless value. Since X can be estimated and calculated, M is computable from the equation above.

This density independent function is valuable because it eliminates the influence of density on the materials' water content. The two measured parameters are attenuation and phase shift, and they are both related to a substances' permittivity, wave frequency, temperature and bed depth.

These parameters are controllable and measurable during the process. Thus, a reasonable moisture content can be obtained from microwave detection and analysis.

Methods

Permittivity and Permeability

Material's dielectric properties---permittivity and permeability, are the parameters that describe the materials' interaction with electromagnetic fields. The permittivity is a measure of how an electric field affects, or is affected by the dielectric medium. It consists of a real part ϵ', called the dielectric constant, and an imaginary part $\epsilon^{"}$, called the loss factor. Therefore, the permittivity is expressed as

$$\epsilon^* = \epsilon' - j\epsilon^{"} \tag{3}$$

The dielectric constant reflects the ability of a material to store electric energy, while the loss factor describes the loss of electric field energy in the material. The relative permittivity is the other expression often used to represent a material's permittivity:

$$\epsilon_r^* = \frac{\epsilon^*}{\epsilon_0} = \frac{\epsilon'}{\epsilon_0} - j\frac{\epsilon^{"}}{\epsilon_0} \tag{4}$$

where $\epsilon_0$is the permittivity of free space and has a value of $8.854 \times 10^{-12} F/m$.

The permeability (μ) is the measure of the ability of a material to support the formation of a magnetic field within itself. In other words, it is the degree of magnetization that a material obtains in response to an applied magnetic field.

Plane wave in Dielectric Medium

The propagation constant of an electromagnetic wave is a measure of the change undergone by the amplitude of the wave as it propagates in a given direction. For a plane electromagnetic wave in a lossy dielectric medium, it is defined as

(5)

$$\gamma=\alpha + j\beta$$

where α is called the attenuation constant, and β is the phase constant. A typical sample of iron ore slurries usually consist of magnetite, hematite, calcium carbonate, magnesium carbonate, siderite, silica, alumina, and free water and they can be assumed as the dielectric medium.

Assumptions

Before further analysis, an assumption needs to be made. Since the permittivity value of water is much larger than other materials' at temperature of 298K and wave frequency of 1 to 2.5 GHz, we can eliminate the effect of other materials' permittivity on the measured value from the signal detector. That is, the measured signal is the water's permittivity only.

In addition, the magnetic property of magnetite may have some uncertain interactions with the electromagnetic field. It is also the main component of a taconite aggregate, as shown in Table1. However, due to the low dielectric constant of magnetite, we temporarily ignore its influence.

Table 1. Taconite Composition on Dry Weight Basis
(Water is between 9wt% to 10wt% of the total mass)

Material	Concentration
Fe_3O_4	90.03
Fe_2O_3	5.95
SiO_2	3.65
Al_2O_3	0.05
CaO	0.11
MgO	0.20

For a nonmagnetic material, when its permeability at a magnetic field equals to the vacuum permeability ($\mu^* = \mu_0$), the two components of the propagation constant can be rewritten as

$$\alpha = \frac{2\pi}{\lambda}\sqrt{\frac{\epsilon_r}{2}\left(\sqrt{1+\ (\tan\delta)^2}-1\right.} \quad (6)$$

$$\beta = \frac{2\pi}{\lambda}\sqrt{\frac{\epsilon_r}{2}\left(\sqrt{1+\ (\tan\delta)^2}+1\right.} \quad (7)$$

For the material with the condition $\epsilon'^2 >> \epsilon''^2$, attenuation constant and phase constant are simplified as:

(8)

$$\alpha \cong \frac{\pi}{\lambda}\frac{\epsilon''}{\sqrt{\epsilon'}}$$

$$\beta \cong \frac{2\pi}{\lambda}\sqrt{\epsilon'} \quad (9)$$

There are data available on the dielectric properties of conductivity water over a wide range in temperature and frequency (Von Hipple, 1954b, p. 361). Results for a frequency of 2.45 GHz are presented in the following table:

Table 2. Dielectric and microwave attenuation properties of water at 2.45 GHz

Temp. (°C)	ϵ'	$(\tan\delta)$	α (m-1)	α^{-1}(mm)
1.5	80.5	0.310	70.6	14.2
5	80.2	0.275	62.7	16.0
15	78.8	0.205	46.5	21.5
25	76.7	0.157	35.2	28.4
35	74.0	0.127	28.0	35.7
45	70.7	0.106	22.9	43.8
55	67.5	0.0890	18.8	53.3
65	64.0	0.0765	15.7	63.7
75	60.5	0.0660	13.2	75.9
85	56.5	0.0547	10.6	94.8
95	52.0	0.0470	8.7	115

Attenuation

From basic electromagnetic theory, it is well known that the power that propagates through a material must decrease according to the factor $e^{-2\alpha d}$, and if the power at x=0 is P_0, then at x=d the power is give, assuming no reflection, by

$$P = P_0 e^{-2\alpha d} \quad (10)$$

Therefore, the layer attenuation is expressed in decibels as the total decrease in power:

$$A = -20\log\frac{P}{P_0} = -10\log(e^{-2\alpha d}) \quad (11)$$

where d is the thickness of the layer (depth of bed).

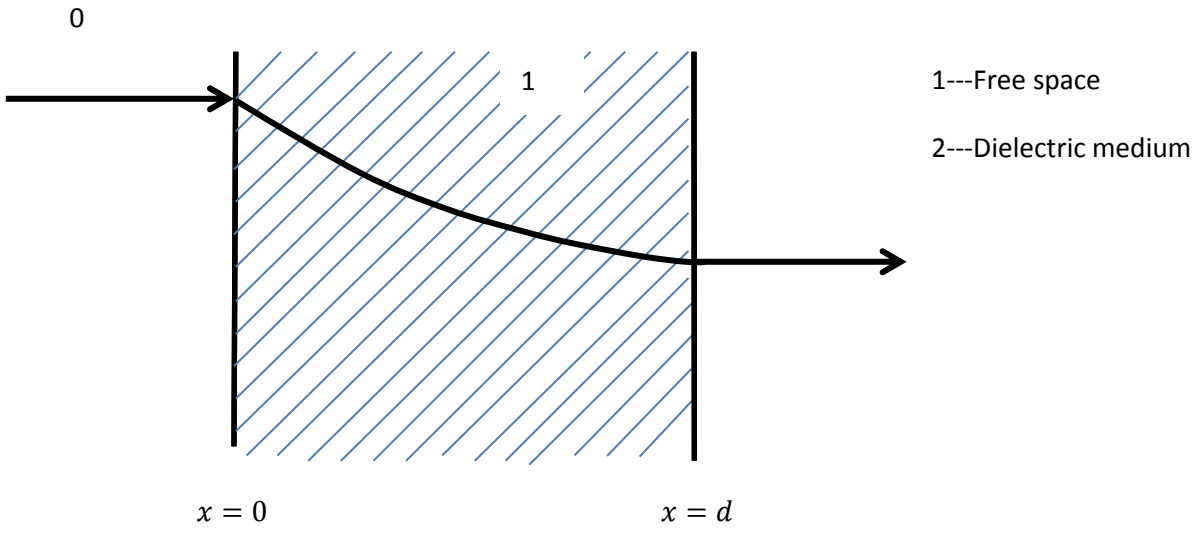

Figure 2. Microwave passing through a dielectric medium

The attenuation constant can be directly read from Table 1 at temperature equals to 25 °C. Therefore, if 2.45 GHz is an attainable microwave frequency, attenuation A can be calculated easily.

Phase Shift

The phase shift is determined from the initial and final measurement of the wave phase angle in the reference plane, $x = d$. The change in phase angle caused by introducing the material layer in the path of the traveling electromagnetic wave can be written as

$$\phi = \phi_1 - \phi_0 = (\beta_1 - \beta_0)d \tag{12}$$

Substitute equation 1, ϕ is rewritten as

$$\phi = \frac{2\pi}{\lambda}\left(\sqrt{\epsilon_1} - \sqrt{\epsilon_0}\right)d \tag{13}$$

where λ is the wave length, ϵ_1 is water permittivity value with the microwave passing through dielectric medium, and ϵ_0 is water permittivity at free space.

Results

With known attenuation and phase shift, ratio X is:

$$X = \frac{A}{\phi} = \frac{-10\log(e^{-2\alpha d})}{\frac{2\pi}{\lambda}\left(\sqrt{\epsilon_1} - \sqrt{\epsilon_0}\right)d} \tag{14}$$

and

$$\frac{1}{X} = \frac{\frac{2\pi}{\lambda}\left(\sqrt{\epsilon_1} - \sqrt{\epsilon_0}\right)d}{-10\log(e^{-2\alpha d})} \tag{15}$$

Substitute this expression into Eq 1, we finally have:

$$\frac{1}{X} = \frac{\frac{2\pi}{\lambda}\left(\sqrt{\epsilon_1} - \sqrt{\epsilon_0}\right)d}{-10\log(e^{-2\alpha d})} = C_1 \times M + C_2 \tag{16}$$

With measured permittivity of water, permittivity in free space, bed depth and certain microwave frequency, we should be able to calculate the corresponding moisture content of the sample.

Monte Carlo Uncertainty Analysis

The expected confidence interval for a moisture analysis was estimated from a Monte Carlo simulation of the propagation of uncertainty in the model inputs on the uncertainty in the relative moisture of a sample. The fixed uncertainties in each model parameter are listed in the table.

Table 3. Averages, fix uncertainties and readabilities of different model parameters

	Average	Fix u	Readability
α (m^{-1})	35.2	0.028868	0.1
d (m)	0.2	0.031754	0.1
λ (m)	0.13	0.002887	0.01
ε_1'	76.7	0.028868	0.1

The Monte Carlo analysis was performed with Dr. Davis' macro UNMCLHS in Excel for Monte Carlo Uncertainty with Latin Hypercube Sampling. The results are shown in the following figure. The model should give a moisture result within ±6.4% 95% confidence.

X	38.187283		
Monte Carlo Uncertainty analysis			
$U_{95\%}$ = -	2.4E+00	= -	6.32%
$U_{95\%}$ = +	2.4E+00	= +	6.34%
Bin	Frequency		
33.64533	1		
34.66607	20		
35.6868	186		
36.70754	1080		
37.72828	2416		
38.74901	2876		
39.76975	2295		
40.79049	966		
41.81122	142		
42.83196	18		
43.8527	0		

Figure 3. Monte Carlo simulation

Running another Dr. Davis' macro JITTER in Excel, the effect of 4 parameters listed above on the ratio is estimated. As can be seen, the wave length has the largest influence on X value.

$U_{95\%}$ = ±	3.6E+00	= ±	9.507%
u_{max} = ±	1.9E+00	= ±	5.025%
u = ±	1.9E+00	= ±	4.845%
$t_{95\%}$ =	1.96	DoF =	1000
c_1 =	1.08E+00	$(c \cdot u_1)^2$ =	0.14%
c_2 =	-1.12E-13	$(c \cdot u_2)^2$ =	0.00%
c_3 =	2.86E+02	$(c \cdot u_3)^2$ =	99.86%
c_4 =	0.00E+00	$(c \cdot u_4)^2$ =	0.00%

Figure 4. JITTER method

Conclusions

Moisture level of iron ore slurries is essential to mineral processing. From filtering slurry to rolling ore concentrate—moisture levels must be constantly tested and regulated to ensure the best quality end product is achieved. With accurate and instant measurement, the quality of an iron ore production process will be improved.

With two assumptions, the influence on measured permittivity from other oxides is eliminated and it narrows down the scope only to water permittivity and the physical settings of the process. The propagation constant bridges the measured permittivity ϵ' to attenuation constant α and phase shift constantβ. Furthermore, attenuation A and phase shift ϕ are acquired. Finally, substituting the ratio of attenuation and phase shift to the linear model, the expression of moisture content in iron ore is obtained and it is dependent on temperature, bed depth, microwave frequency, and permittivity.

However, there may be limitations associated with the effect of magnetite in electromagnetic field and parameters in the linear model. Specifically, since the magnetite corresponds to 80 wt. % of a taconite aggregate, its influence may not be ignored. In addition, it is almost impossible to simulate the real production process in a university setting; therefore, the parameter C_1 and C_2 cannot be decided at the point, but should be determined from correlation of experimental data.

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